LEACHATE RECYCLE AT SOLID WASTE LANDFILLS USING HORIZONTAL INJECTION

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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A method of leachate recycle known as horizontal injection was examined. In this method, leachate is recirculated to a landfill through horizontal trenches or wells buried within the landfill. Potential advantages of a leachate recycle system of this nature include the ability to recycle leachate to the landfill without atmospheric exposure, the ability to control the point of leachate recycle and the resulting moisture distribution, and the ability to lessen impact of leachate recycle on daily landfill operations.

Analytical equations were developed to describe the expected shape of the saturated zone surrounding an injection line for both isotropic and anisotropic conditions. The equations were developed by treating an injection line as a

line source in a porous medium subject to a gravity drainage flow field. Capillary forces and dispersion were neglected. The equations allowed prediction of the horizontal and vertical spread of the saturated zone and the resulting injection pressure as a function of injection line length, flow, and waste hydraulic conductivity.

A horizontal injection leachate recycle system (HI-LRS) was constructed and operated at a Florida landfill. The system consisted of perforated pipes placed in shredded tire filled trenches and buried between lifts of compacted solid waste. The performance of 11 injection lines was evaluated. During a period of 19 months, 7.9 million gallons of leachate were recycled to the landfill through the injection system. Pressures and flows observed during the injection were recorded. Typical injection flow responses ranged from 0.005 to 0.007 gpm/ft per foot (water column) of applied pressure head in trenches with shredded tires as a drainage blanket. In trenches without tires, flow rates ranged from 0.004 to 0.005 gpm/ft per foot of applied pressure head. Injection at high pressures did result in some surface seeps from injection lines located near the surface of the landfill.

CHAPTER 1
INTRODUCTION

Leachate recycle, also referred to as leachate recirculation, is a method of managing leachate at solid waste landfills. This process involves the return of leachate intercepted by a landfill's liner and leachate collection system back to the landfilled solid waste. Benefits cited for leachate recycle include leachate volume management, leachate treatment, accelerated landfill stabilization, and enhanced gas production. Numerous pilot-studies have been performed demonstrating these benefits (Pohland 1975, 1980; Leckie et al. 1979, Buivid et al. 1981).

Leachate recycle has been practiced at full-scale landfills in the United States and Europe (Barber and Maris 1984, Natale and Anderson 1985, Watson 1987) but the results of these projects in regard to the performance and design of various methods of leachate recycle have been limited. The most recent Subtitle D regulations of the Resource Conservation and Recovery Act permit leachate recycle in properly designed landfills (Federal Register 1991), but the practice is discouraged by some state regulators as a result of potential threats from poorly operated systems. Further investigation into the mechanisms involved in various methods

of leachate recycle is necessary to allow safe and effective design of leachate recycle systems at landfills, and for the development of regulations and the transfer of this technology.

This dissertation discusses a leachate recycle process known as horizontal injection and reports its application at an operating landfill in Alachua County, Florida. In this process, leachate is pumped under pressure into horizontal injection lines buried at various depths within the landfill. This method of leachate recycle has a number of potential advantages over other methods including limitation of leachate exposure to the atmosphere, ability to control points of leachate application and leachate distribution, and minimal interference of leachate recycle operation on overall landfill operation.

In Chapter 2 of this dissertation, mathematical equations are developed to describe the shape of the saturated zone surrounding an injection line under steady injection conditions as a function of injected flow rate and the hydraulic conductivity of the medium. Isotropic and anisotropic conditions are considered. Chapter 3 presents information on the design, construction, and operation of the horizontal injection leachate recycle system (HI-LRS) at the Alachua County landfill, and discusses the results and performance of the system. Chapter 4 uses the information in Chapters 2 and 3 to outline construction and operation

guidelines, and a design procedure for use of horizontal injection as a method of leachate recycle at operating landfills. A summary of the dissertation and conclusions reached from the research, as well as areas of additional needed research, are presented in Chapter 5

CHAPTER 2
SATURATED FLOW FROM A HORIZONTAL INJECTION LEACHATE RECYCLE SYSTEM

Introduction

Horizontal injection leachate recycle involves the recirculation of leachate to a landfill through the use of horizontal recharge wells. The wells are buried within the waste, and are usually constructed as the waste is deposited. Horizontal injection leachate recycle systems (HI-LRS) represent a promising technology for leachate and solid waste management at landfills, but such systems are relatively untested and little information is available for their design. This chapter outlines analytical equations which describe the characteristics of steady state saturated flow of water surrounding a horizontal well resulting from the pressure of the injected water and gravity. This chapter was developed in response to, but independent of, a HI-LRS under evaluation at a lined landfill in Florida (Chapter 3).

The method outlined here to model the saturated zone of water which surrounds a horizontal injection well is based on the assumption that the well can be treated as a horizontal line source. The line source is subject to the effect of gravity in the vertical downward direction. A further assumption is made that water movement is not impeded in the

downward direction. This case occurs in lined landfills where a highly conductive collection layer drains leachate from the liner system

Simulation of water flow from line sources buried in soils has been performed in the soil science field in a number of previous investigations (Raats 1970, Philip 1971, Zachmann and Thomas 1973, Thomas et al. 1974). The primary driving force for water movement in these irrigation studies has been the capillary suction of the soil. These analyses have simulated the unsaturated moisture profile resulting from capillary forces, and describe conditions of relatively low flow. The resulting solutions are generally complex analytical equations.

The process outlined here to describe the saturated zone surrounding a horizontal injection well involves the assumption that the primary driving forces for moisture transport are the pressure of the injected water and gravity. If capillary forces and the effects of dispersion are neglected, a simple analytical solution describing the shape of the saturated zone may be determined. The resulting solution is similar to the solution of groundwater recharge through a vertical well in a confined aquifer subject to a uniform field of flow (Bear and Jacobs 1956). The solution of the uniform flow field analysis has also been applied to the development of capture zone equations in the management of pollutant plumes in groundwater (Javendel and Chin-Fu 1986).

The uniform flow field in the vertical well scenario is analogous to the gravity drainage flow field in this analysis. An advantage to the treatment of the flow system in this manner is that a solution for the case of an anisotropic material is readily obtained.

Unsaturated flow and capillary forces certainly play a role in moisture transport under typical landfill conditions. In the scenario outlined, a capillary fringe of water would develop surrounding the saturated zone. The equations outlined here are not intended to provide a method of conducting complex water balance and moisture routing simulations for landfills with LRS. Numerical models which incorporate saturated and unsaturated flow and which account for the complexities of multiple well systems are necessary. It is proposed is this chapter, however, that for purposes of establishing design boundaries for efficient and safe HI-LRS operation at maximum flow conditions, saturated flow hydraulics can be used to estimate requirements for injection well spacing, depth, pressure requirements, and leachate collection system design.

Equation Development

A schematic of the flow system evaluated is presented in Figure 2-1. The horizontal well is located with its center at the origin and is represented by a line source. The well consists of some finite radius (r_w). Water is injected into the well at a flow rate of q, which represents the linear

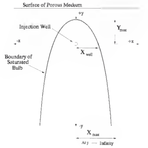


Figure 2-1 Saturated Flow Zone Surrounding a Horizontal Injection Well Flow System under Steady Conditions

flow rate (flow per unit length of wall). Under steady conditions, a saturated zone will form around the injection wall, reaching some maximum height above the wall, Y_{max}. At Y_{max}, the potential of a fluid particle to move away from the well is equal to the potential created by gravity to move toward the wall, and a stagnation point develops. It is assumed that flow may continue beneath the wall without resistance. The width of the saturated front at an infinite downward distance is $2X_{max}$. The distance from the origin to the edge of the saturated bulb at the elevation of the wall is defined as X_{wall}.

Flow in Isotropic Medium

The system of saturated flow from a horizontal well in an isotropic medium is solved by the method of superposition in which the solutions of two simple flow fields are superimposed. The first field consists of flow from a radial line source and the second field is gravity drainage. The potential function for a radial line source is

$$\phi = -\frac{q}{2\pi K}\ln(r) \qquad 2\text{-}1$$

where ϕ is the potential, k is the hydraulic conductivity of the medium, and r is the radial distance from the line source.

The potential field created by gravity may be considered saturated drainage at a unit gradient. It is also assumed to representad the gravity field under conditions where saturated conditions do not occur, but where capillary forces and

dispersion are neglected. Therefore, in the gravity drainage scenario, the potential gradient is 1, and

$$\frac{\partial\phi}{\partial y} = 1 \ , \quad \frac{\partial\phi}{\partial x} = 0 \qquad 2\text{-}2$$

The solution for the potential function for the case of gravity drainage may therefore be written as

$$\phi = y \qquad 2\text{-}3$$

The two flow scenarios may be combined using the method of superposition. The variable r is converted to axisymmetric coordinates ($r^2 = x^2+y^2$).

$$\phi = \frac{q}{2\pi k}\ln(\sqrt{x^2+y^2}) + y \qquad 2\text{-}4$$

A stagnation point occurs at Y_{max}. At this point, a singularity of zero flow develops where the potential gradient in the vertical direction is zero. The value of Y_{max} may therefore be determined by solving Eqn. 2-4 when x = 0, and $d\phi/dy = 0$. This results in

$$Y_{max} = \frac{q}{2\pi k} \qquad 2\text{-}5$$

The conjugate function of the potential function is the stream function, which describes the flow paths of fluid particles from the injection well. The stream function, may

be determined for a horizontal injection well with the relationship

$$\psi = \frac{\partial \phi}{\partial y} dx \qquad 2\text{-}6$$

such that,

$$\psi = \frac{q}{2\pi k} \tan^{-1}\left(\frac{x}{y}\right) + x \qquad 2\text{-}7$$

The boundary for the saturated bulb occurs where $\psi = 0$, and this relationship may therefore be determined as

$$\frac{x}{y} = \tan\left(\frac{x2\pi k}{q}\right) \qquad 2\text{-}8$$

The value of X_{max} may be determined by evaluating Eqn. 2-8 for conditions when y approaches $-\infty$.

$$X_{max} = \frac{q}{2k} \qquad 2\text{-}9$$

From Eqn. 2-8, the value of X_{well} may be determined at the boundary where y = 0.

$$X_{well} = \frac{q}{4k} \qquad 2\text{-}10$$

In an isotropic medium, the stream lines will be perpendicular to the lines of equal potential. An example flow net for the saturated flow conditions surrounding the horizontal injection well is presented in Figure 2-2.

Flow in Anisotropic Medium

Often it is necessary to account for anisotropic conditions in a porous medium. This is especially true in

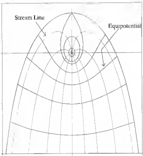


Figure 2-2. Equipotential and Stream Lines resulting from a Horizontal Injection Well

situations which involve the flow of water in both the vertical and horizontal directions. Many times in natural soils, hydraulic conductivity in the horizontal direction will be greater than in the vertical direction a result of the manner in which sediments are deposited over time. This situation occurs in a landfill where waste is deposited and compacted in horizontal layers. Equations for the saturated zone surrounding a horizontal injection well in an anisotropic medium may be developed using the same method as the isotropic case. It is assumed the material is homogeneous and that axes of anisotropy correspond to the principal axes of the system. The governing equation for the case of steady plane flow is

$$k_x \frac{\partial^2 \phi}{\partial x^2} + k_y \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad \text{2-11}$$

where k_x and k_y are the hydraulic conductivities in the x and y direction, respectively. The anisotropic problem may be solved by means of an equivalent isotropic flow region by an appropriate scale change. The method has been previously outlined by Bear and Dagan (1965). The solution of the potential function for a line source in an anisotropic medium using the method of an equivalent isotropic flow region was presented by Carslaw and Jaeger (1959). When combined with Eqn. 2-3 by the method of superposition, the resulting potential function for an injection well in an anisotropic medium is

$$\phi \quad \frac{q}{4\pi\sqrt{k_x k_y}} \ln\left(\frac{x^2}{k_x}+\frac{y^2}{k_y}\right) + \qquad 2\text{-}12$$

Using the same techniques applied in the isotropic case, the equation of the saturated zone may be determined as

$$x = \frac{q}{2\pi k_y} \tan^{-1}\left[\frac{x}{y}\sqrt{\frac{k_y}{k_x}}\right] \qquad 2\text{-}13$$

The parameters Y_{max}, X_{max}, and X_{well} may be determined as

$$Y_{max} = \frac{q}{2\pi\sqrt{k_x k_y}} \qquad 2\text{-}14$$

$$X_{max} = \frac{q}{2k_y} \qquad 2\text{-}15$$

$$X_{well} = \frac{q}{4k_y} \qquad 2\text{-}16$$

The distances X_{max} and X_{well} are a function of the hydraulic conductivity in the vertical direction only. The location of the stagnation point above the well, Y_{max}, is function of hydraulic conductivity in the vertical and horizontal direction, and thus varies for differing degrees on anisotropy. The effect of the degree of anisotropy on the shape of the saturated bulb is illustrated in Figure 2-3.

Injection Flow and Pressure Relationship

An additional parameter of interest in a horizontal injection well system is the injection pressure required for a given flow rate in a given set of medium conditions. The

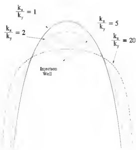


Figure 2-3. Effect of Anisotropy on Saturated Boundary

pressure head required, P_h, may be defined for isotropic conditions as

$$P_h = \frac{q}{2\pi K}\ln\frac{R}{r_w} \qquad 2\text{-}17$$

and for anisotropic conditions as

$$P_h = \frac{q}{2\pi\sqrt{K_x K_y}}\ln\frac{R}{r_w} \qquad 2\text{-}18$$

where r_w is the effective well radius and R is the radius of influence of the line source. In the mathematical relationship for a line source, the radius of influence continues outwards towards infinity. It is therefore necessary to assume some radius at which the effect of the line source is negligible. In the case of a horizontal injection well, this may be viewed as the distance beneath the well at which the effect of the well is no longer observed. The radius of influence may be selected in the same manner as typical well hydraulics using empirical or semi-empirical estimates (Bear 1979). These estimates often vary widely and P_h should be evaluated for a range of R values.

Leachate Flow to the LCS

The flow of leachate into the landfill bottom drainage layer is a critical part of the design of the leachate collection system (LCS). If the LCS was located at an infinite distance beneath an injection line, then the flow into the LCS would be equal to the injected flow rate.

However, the closer the LCS is located to the injection line, the greater the flow rate per unit area. The flow rate for a given area of the flow net may be determined from the difference between the stream function lines, which may be estimated using Eqn. 2-7.

Discussion

The steady state equations presented here allow an estimation of the shape of the saturated flow zone that results from a horizontal injection well in a landfill which drained by a LCS. Graphs presenting the change in Y_{max}, X_{well}, and P_h as a function of the linear flow rate and the hydraulic conductivity are presented in Figure 2-4, 2-5, and 2-6 respectively.

The greatest limitation to the application of this analysis is the neglect of unsaturated flow conditions. Unsaturated flow does occur in a landfill, and is the predominant means of moisture transport for low moisture flux conditions. In the case of a horizontal injection well under pressure at steady state, the forces of pressure and gravity will be the dominant transport mechanisms in the area surrounding the well. A zone of moisture transport will occur in the area surrounding the saturated zone as a result of capillary forces, and may affect the shape of the zone. At larger pressures, the potential created by hydrostatic pressure should be much greater than from capillary potential.

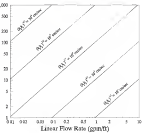


Figure 2-4. Y_{max} as a Function of Linear Flow Rate

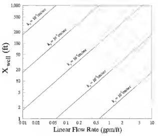


Figure 2-5. X_{well} as a Function of Linear Flow Rate

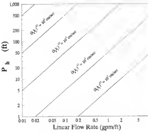


Figure 2-6. Pressure Head as a Function of Linear Flow Rate (R/r_w = 100)

The above equations were developed to allow design under maximum flow conditions which might be encountered in HI-LRS operation. For example, seepage into the LCS will be at a maximum when a saturated zone develops surrounding an injection well and reaches into the LCS. Although planned LRS operation may not reach steady state, the maximum possible conditions should be designed for to accommodate future operating conditions.

Conclusion

Equations were developed to describe the shape of the saturated zone surrounding a horizontal injection well under steady state conditions. The injection well was treated as a line source subjected to a gravity drainage flow field, and capillary forces and dispersion were neglected. Solutions were presented for isotropic and anisotropic cases. The predominate driving forces of water movement were assumed to be the pressure of the injected water and gravity. The method of analysis outlined here is proposed as a method to establish design criteria for the application of a HI-LRS at full-scale landfills. The equations allow a means to design injection well spacing, and the depth from the surface at a given flow rate. An estimate of the pressure head, which is necessary to properly size the pump and piping system, can be obtained as well.

CHAPTER 3
LEACHATE RECYCLE USING HORIZONTAL INJECTION
AT A FLORIDA LANDFILL

Introduction

Leachate recycle involves the recirculation of leachate collected from a lined landfill back through the landfilled waste. This practice provides leachate volume management and offers the potential to accelerate the decomposition of biodegradable waste in a landfill. Leachate recycle has been successfully demonstrated in pilot-scale studies to enhance waste stabilization (Leckie et al. 1979, Pohland 1980), and has been practiced at a number of full-scale landfills with some positive results (Harber and Marie 1984).

The recycle of leachate to a landfill may be performed by a number of methods including spray irrigation, surface application, and direct recharge to the interior of the landfill. Vertical recharge wells have been utilized to recycle leachate, but the resulting distribution of moisture through the waste is questionable. Horizontal injection wells offer the potential to distribute moisture over large areas of a landfill, while avoiding the problems associated with leachate exposure to the environment such as migration of odor and aerosols. Horizontal injection wells minimize

interference with normal landfill operations and vehicle and equipment traffic. The recycle of leachate through horizontal distribution systems has been briefly mentioned in other studies (Natale and Anderson 1985), but no detailed study of their construction and performance has been reported.

This paper presents the results of a horizontal injection leachate recycle system (HI-LRS) at a lined landfill in Florida. The construction, operation, and performance of eleven injection lines, are reported for a period from February, 1993 through August, 1994. The information is presented to facilitate the use of this technology at other landfill sites, and provides information relevant to the construction and operation of HI-LRS and the design of such systems. The effect of the HI-LRS on a number of additional landfill parameters, including leachate generation and composition, waste decomposition, landfill temperature, and gas production, were monitored at this research site, and will be reported elsewhere.

Methods

Site Description

The horizontal injection leachate recycle study was performed at the Alachua County Southwest Landfill (ACSWL) in North Central Florida (Figure 3-1). The 27-acre (11-hectare) landfill is lined with a composite liner and is equipped with a leachate collection and removal system. Leachate drains

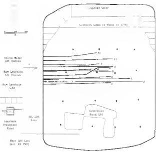


Figure 3-1. Plan View of ACSWL with Injection Lines

from the landfill to a lift-station and is pumped to a leachate equalization-treatment plant. The landfill includes an aeration and lime-precipitation leachate treatment system. Treated leachate is hauled off-site for disposal at a waste water treatment plant. An infiltration pond leachate recycle system (LRS) was operated beginning in 1990 (Townsend et al. In press a) as part of a project involving the accelerated stabilization of the landfilled waste (Townsend et al. In press b)

The site receives an average of 60 inches of rain annually. Approximately 330 tons per day of waste were deposited in the lined landfill unit at the time of this research. Apparent waste compaction is approximately 1070 to 1310 lb/yd^3. Cover soil consists of sand mined on site. Waste is deposited in a set of four lifts which are placed in an east-west fashion and which slope upward to the south against the previous set of lifts.

LRS Construction

The construction of horizontal injection lines (HIL) began in December 1991 on a series of four lifts constructed north of the infiltration pond LRS. Three injection lines were placed in this series of lifts, the first on top of lift 1, the second on top of lift 2, and the third on top of lift 3. The result was a staggered positioning in which the first injection line was the northernmost and positioned at the lowest elevation, and the third injection line was the

southernmost and at the highest elevation. Upon completion of one set of injection lines, another set of three lines was placed in the next series of lifts in a similar fashion. The resulting cross section is shown in Figure 3-2, displaying the position of the injection lines in place at the end of August 1994, eleven of which were used and discussed here.

The characteristics of each HIL are listed in Table 3-1. The length and location of each injection line was dependent on the available area of lift. The design pipe diameter for the leachate recycle piping system was 3-inches, and this diameter was used for the injection lines as well. Holes were drilled in the injection pipe before installation. The hole size and spacing in the original injection line were designed to distribute flow evenly throughout the trench. It was felt that resistance to injected leachate would most likely result from the solid waste surrounding the trench, and the trench would fill with leachate under pressure, obviating the need for distributed flow from the pipe. The later injection lines (HILs 3-11) were therefore over designed (with additional holes) to accommodate for potential fouling and clogging.

PVC pipe was selected for the majority of the injection lines because of ease and quickness of installation. The PVC pipe was affixed with cement during installation. A high density polyethylene pipe was installed for HIL 7 and was fusion-welded prior to installation. The length of each injection line placed was dictated by the length of individual

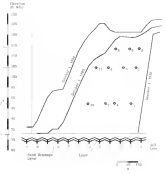


Figure 3-2. Cross Section of Injection Lines

Table 3-1. Injection Line Characteristics

HIL	Date of Construction	Pipe Material	Pipe I.D. (ft)	Length of Injection Pipe (ft)	Hole Size (in)	Hole Spacing	Drainage Material	Average Elevation (ft MSL)
1	Jan 92	PVC	0.25	650	0.19	a	Tire Shreds	87
2	Mar 92	PVC	0.25	780	0.25	b	Tire Shreds	104
3	May 92	PVC	0.25	540	0.25	c	Tire Shreds	113
4	Jul 92	PVC	0.25	360	0.31	c	Tire Shreds	87
5	Jul 92	PVC	0.25	520	0.31	c	Tire Shreds	104
6	Sep 92	PVC	0.25	540	0.31	c	Tire Shreds	113
7	Dec 93	PVC	0.25	360	0.31	c	Tire Shreds	87
8	Jan 93	PVC	0.25	520	0.31	c	Tire Shreds	104
9	Feb 93	PE	0.25	540	0.31	c	Tire Shreds	113
10	Apr 93	PVC	0.25	360	0.31	c	None	87
11	Apr 93	PVC	0.25	520	0.31	c	None	104

[a] Varied Spacing; 1 hole per 5 ft average.
[b] One hole every two feet.
[c] Two holes every two feet.

lifts at the time of installation. Injection lines 1 and 2 were constructed to cross the entire bottom length of the landfill (650 ft and 780 ft, respectively). This necessitated building the lines in phases because the entire lift lengths were not constructed during one time period. The practice of phased construction required precise coordination of waste placement and re-excavation of part of the trench. To minimize these difficulties, the remaining injection lines were constructed in one phase, utilizing the length of lift available.

Construction of the injection trenches for lines 2 through 11 were conducted with a backhoe, which was used to excavate a trench down the center of the lift from west to east. The trench for NIL 1 was constructed using a bulldozer, which resulted in a much larger trench volume. The backhoe trenches were approximately three feet square, and the excavated waste and cover material were placed to the side of the trench. Shredded tires were used as drainage material in injection lines 1 through 9. The tires were placed at the bottom of the trench to a depth of approximately 1 foot. Tires were not placed in lines 10 and 11 for comparison of injection performance.

The pipe was placed in the trench and glued. An additional one to two feet of shredded tires (if used) were placed on top of the pipe and spread evenly. The terminal end of the pipe was capped. Non-perforated pipe was installed in

the first 60 ft of trench and no tires were placed in this area of the trench to prevent channeling along the pipe. This trench area was covered only with waste. The injection lines were connected to non-perforated riser pipes up the side slope of the landfill. The injection line area of the trench was covered with excavated waste and compacted using a progression of equipment, from light to heavy. An effort was made to keep the trenches covered on all sides with waste, and not cover sand, which could lead to short circuiting of injected leachate.

Leachate injection lines were connected to a main LRS manifold line which ran along the western outer landfill berm to the LTP and two submersible stainless steel well pumps (2 hp and 3 hp) in the raw leachate equalization basins. Each HIL was valved separately to allow injection into any desired lateral. The pumps were valved to allow independent and parallel operation.

System Operation and Monitoring

Two parameters were measured to assess the hydraulic performance of the system, leachate flow and pressure. Flow was measured using a paddle-wheel flow meter transducer (analog output) installed in the main manifold line on the berm. Pressure was measured with an analog output pressure transducer located in the manifold line on the landfill berm 50 ft before the first HIL. Analog signals were recorded by

data loggers in the field which were periodically downloaded to a portable computer.

Injection Schedule

The application of leachate to various injection lines, and the frequency and rate of application, were dictated by a number of factors. These factors included research goals of monitoring the effect of the LRS on the landfill system, the volume of water available for injection, and the schedules of the landfill operating crew. The injection of leachate was suspended at times to allow the landfill system to be monitored and for the repair and maintenance of the HI-LRS. All of the injection data reported here involved leachate recycle into one injection line at a time.

Initial injection tests were conducted during February through April 1993, using injection lines 1 and 2. During the initial test period, leachate was injected for prolonged periods to observe the physical operating constraints of the system. The next round of injection tests began in September 1993, and from that time leachate was injected on a daily basis, at a maximum of 60,000 gallons per day. This limit was an arbitrary level established by the landfill's permitting authority. The schedule of injection during the period from September 1993 to January 1994 consisted of rotating injection into lines 1 through 6 at approximately 45,000 gallons per day for two or three days into each line. In the spring and summer of 1994, leachate injection began into lines 7, 8, 9,

10, and 11, with continued limited injection into lines 1 through 6

Results and Discussion

HIL Construction

Construction of the HI-LRS was performed by landfill operators using typical landfill equipment. The most noticeable difficulties encountered in HIL construction were timing of HIL construction and odors resulting from excavated waste. Because the injection lines were constructed between lifts of waste, the available construction time was often only a matter of days. This was especially true in the cases where the end phase of the lower lift, the beginning phase of the upper lift, and the inlet section of an HIL coincided. In these cases, HIL were often constructed in the presence of other landfill vehicles. The location of the trench on the surface of the lift was determined by considering the location of the limerock roads, the proximity to large cover soil layers, the proximity to vertical gas wells, and the slope available for the backhoe to excavate the waste. Although a rubber-wheeled backhoe was used at ACSWL, a back-hoe on track would have allowed more flexibility for HIL placement in areas of steeper slopes.

The trenches were excavated in a manner designed to avoid direct contact with thick lenses of cover material which would result in short-circuiting. Complete exclusion of these lenses was impossible. Covering the trench with solid waste

and compacting the area above the trench required constant attention of the landfill operator to ensure sufficient waste was on top of the line before heavy equipment was used. The shredded tires did act as adequate bedding and cover for the pipe in this process.

Odor presented a problem when large areas of trench were left open for periods of time greater than 12 hours. This was controlled by installing the drainage material and pipe during or immediately after trench excavation in such a manner as to assure that no trench area was left open more than 12 hours.

The injection lines were checked for integrity prior to use. Of the first 11 injection lines, two were found to be obstructed. These NIL were each in the upper level and in the non-perforated pipe section. This area of the injection system was most vulnerable to damage from vehicles and heavy equipment because of the proximity of the pipe to the landfill surface and access roads. Injection lines on the lower levels were generally covered with large thicknesses of waste soon after completion, and traffic was not a problem for these. The proximity to the surface, did however, permit excavation and repair of damaged pipe sections. The obstructions were the result of landfill equipment or traffic crushing pipe and both occurred near the major access road for solid waste delivery vehicles. After the initial spring 1993 test period, a blockage was discovered in NIL 1 at 400 ft during the installation of a temperature probe.

While a detailed analysis of the materials used in the HIL construction was not performed in this study, it should be considered in the design of such a system. The presence of landfill equipment and the occurrence of differential settlement create conditions that can cause pipe breaks. Differential settlement presents the greatest risk to pipe breakage in lines constructed over large thicknesses of waste. The greatest concern at ACSWL was a break in the pipe in the non-perforated riser section, because such a break would result in loss of use of that line. A pipe break in the perforated section of the pipe presented less of a concern in the event of a break, the tires would still allow some hydraulic transmission.

Landfill settlement did result in stress at the piping connections of the HIL and the HIL manifold. This resulted in some leaks in valves and connection. Future construction should include flexible hose connections to replace any rigid connections between pipes inside the landfill and pipes outside the landfill.

Leachate Recycle Volumes

A total of 7,900,000 gallons of leachate were recycled using the HI-LRS during the period from February 1993 to August 1994. The total volume of leachate injected into each

Table 3.2 Injection System Results

MIL	Start Injection	Total Hours of Injection	Total Volume Injected (gallons)
1	Feb 4, 93	513.3	2,364,500
2	Mar 27, 93	260.1	1,027,100
3	Sep 15, 93	54.4	276,800
4	Oct 12, 93	170.5	843,600
5	Oct 1, 93	157.0	804,600
6	Sep 17, 94	61.5	263,000
7	Mar 3, 94	223.1	1,096,500
6	May 5, 94	133.6	616,000
9	Jun 8, 94	31.3	136,000
10	Jul 5, 94	57.2	249,000
11	Jul 15, 94	53.0	215,000
Total	--	1715.0	7,916,300

line during this period is presented in Table 3.2. The greatest volume of leachate was injected into HIL I, primarily as a result of the initial injection period in the spring of 1993. As a result of the length of this line, and the large trench volume, the initial conditions offered little resistance to flow. Overall, greater volumes of leachate were recycled to HIL constructed on the lower and middle lifts relative to HIL on the top lifts. The operation of the injection system in these upper lines resulted in occasional surface springs at the flow rates and pressures created by the leachate recycle pumps. The seeps occurred at points closest to the western end (inlet) of the perforated pipe section, and resulted from short circuiting through more conductive soil material or channels created by previous auger borings.

Pressure Flow Relationship

The leachate flow rates and pressures in the main manifold were recorded for each injection run. A typical flow and pressure response occurring during an injection period is presented in Figure 3-3. The flow rate started at the highest value, and decreased towards a steady rate. The pressure started at a low value and tended towards a higher steady value. The slight decrease in pressure at steady state conditions was the result of dropping leachate levels in the leachate storage tanks. The degree of this change and the time to reach a steady value were a function of the volume of leachate previously injected, the degree of saturation

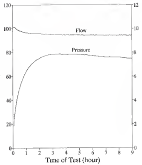


Figure 3-3. Typical Injection Flow and Pressure Response

resulting from any nearby injection lines, and the total storage volume in the trench

The leachate flow and pressure responses were recorded for each HIL as a function of calender time and cumulative pumping time, and those results are presented in Appendix A. To factor indifferences in HIL length and to estimate the actual applied pressure at the inlet of the perforated section of an HIL, flow and pressure at the metering point were converted to linear flow rate (gpm per foot of injection line) and applied pressure head (feet of water column). The applied pressure was estimated from the pressure recorded in the line at the pressure gage, the average elevation of the line, and expected head loss from the pressure gage to the HIL inlet. Figure 3-4 presents the linear flow rate and applied pressure head for HIL 7, a line which received a total of 1.1 million gallons of recycled leachate. The data are presented as an average of 0.1 day time increments. The pattern of decreasing flow and increasing pressure at later time periods was observed in the long term trend results as well The results are presented in Appendix A for each HIL.

The flow rate which occurs at a given applied pressure provides information regarding the performance of the system, its change over time, and is data needed for the design of similar systems. A parameter κ is defined to represent the ratio of linear flow rate (gpm/ft) to the applied pressure head at the inlet of a HIL (ft w.c.).

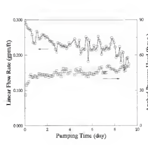


Figure 3-4. Linear Flow Rate and Applied Pressure Head versus Time: HIL 7

Table 3.3. Average Injection Flow Rates and Applied Pressure

SIL	Flow Rate (gpm)	Average Linear Flow Rate (gpm/ft)	Average Applied Pressure Head (ft w.c.)	Average Kappa (gpm/ft/ft)
1	78.0	0.120	49.3	0.00243
2	71.8	0.092	25.6	0.00362
3	84.8	0.157	15.7	0.01002
4	77.4	0.215	41.9	0.00514
5	85.3	0.164	23.7	0.00694
6	79.4	0.147	13.0	0.01133
7	79.6	0.221	43.4	0.00509
8	77.0	0.148	25.0	0.00594
9	72.4	0.134	15.0	0.00897
10	72.7	0.202	49.0	0.00411
11	69.2	0.130	28.3	0.00460

The average results of flow rate, linear flow rate, applied pressure head, and κ, are presented in Table 3-3 for each HIL. The results represent averages for the entire period of injection, with exception of HIL 1 and 2, which do not include the data from the spring 1993 test. While a large volume of leachate was recycledduring the spring 1993 test, a number of the data files were lost, and only one pump was installed during this time. Some pump clogging was observed which proved to provide erratic results in regard to the pressure and flow data (see Appendix A). The value of κ as a function of cumulative pumping time is presented in Figure 3-5 for HIL 4 and 5, Figure 3-6 for HIL 7 and 8, and Figure 3-7 for HIL 6, 9, 10, and 11.

A number of observations were made regarding the pattern of κ as a function of time. The HILs which resulted in the greatest measured flow to pressure responses were those nearest the landfill surface. These were the HILs in which the likelihood of surface springs was the greatest. Two factors likely played a role in this phenomenon. First, it was realistic that the hydraulic conductivity was greater in this area because of smaller effective stress resulting from smaller depths of waste above these injection lines. In addition, the large pressures which occurred in the injection system at ACSWL created apparent waste uplift conditions so that the force of the injected leachate itself created preferential channels. During injection into a surface HIL,

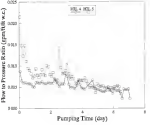


Figure 3-5. κ versus Time: HIL 4 and 5

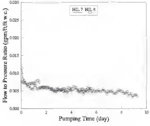


Figure 3-6. κ versus Time: HIL 7 and 8

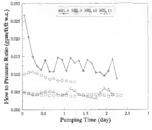


Figure 3-7. κ versus Time   HIL 6,9,10,11

leachate injection was observed to visibly uplift a limerock road with the formation of a surface spring. The results in the upper HILs were the most variable because of this phenomenon and because these lines were operated on a very intermittent basis.

As was previously observed with the flow and pressure relationships over time, the value of k decreased with time as a general trend for all the HILs. A number of potential reasons may be cited to account for this. The initial reduction in flow response was a result of the saturation of the surrounding waste and trench, and the filling of the available storage volume. A potential reason for long term reduction is the occurrence of clogging or fouling of the perforations in the pipe, and the trench itself. Another possibility which was visibly observed at the landfill was the back pressure of landfill gas in the injection lines. At times after an injection run, gas pressures as high as 200 inches of water column were recorded. The higher gas pressures, which would result from increased gas production and reduced void space in the near-saturated waste, would result in reduced relative permeability for water flow through the solid waste. To accommodate long term flow reduction, the ability to operate at higher pressures, and the ability to extract gas should be considered as part of system design.

The most representative flow responses for the injection lines were observed in HIL 4, 5, 7, 8, 10, and 11. These

lines were buried deep enough in the landfill to avoid surface seepage problems. The average κ values in lines 4, 5, 7 and 8 ranged form 0.0051 to 0.0069 gpm/ft/ft w.c.. The average κ values in lines 10 and 11 (no tire drainage material) were 0.0041 and 0.0046 gpm/ft/ft w.c.. The injection system without tires still functioned, although at slightly larger pressures. Construction without tires made the installation process much easier and more rapid for the operator, but a pipe break in one of these trenches would greatly reduce injection performance.

The range of values presented above represents the most typical conditions at ACSWL as measured during the injection experiments and the ones which should provide the best reference for the design of similar systems. It should be noted that the κ values measured were for a specific flow range and extrapolation beyond this flow range may provide incorrect results. Future tests at the ACSWL HI-LRS should include the performance of injection tests at lower flow rates for prolonged periods of time to measure the steady state response of the system

Hydraulic Conductivity Estimation

In a previous chapter (Chapter 2), an equation was presented which related the injection pressure to flow rate for a horizontal well based on line source hydraulics, such that:

$$P_h = \frac{q}{2\pi\sqrt{k_x k_y}} \ln\left[\frac{R}{r_w}\right] \qquad 3\text{-}1$$

where q is the linear flow rate, k_x and k_y are the hydraulic conductivities in the x and y directions, R is the radius of influence for the line source solution, and r_w is the effective radius of the well.

Although the injection tests reported in this paper were not designed to determine the validity of this relationship, the data collected can be used to estimate the magnitude of the hydraulic properties of the waste. An additional fact that makes this exercise useful is that previous tests were conducted in the same landfill using an infiltration pond LRS. The vertical hydraulic conductivity, k_y, was estimated from those experiments at 3×10^{-6} to 4×10^{-6} cm/sec. The injection test data can therefore provide some estimate of the degree of anisotropy. The infiltration pond tests were performed on an area south of the HI-LMP. Exploratory borings in the two areas suggests that the waste compaction was greater in the pond area than in the injection area.

One difficulty encountered in the use of a line source solution is the necessity to assume a value for the radius of influence. Table 3-4 presents hydraulic conductivity estimates for the most representative HILs (4,5,7,8) for values of R/r_w of 100 and 250. Hydraulic conductivity estimates are made for an isotropic assumption, and for anisotropic assumptions with k_y values of 4×10^{-6} cm/sec and

Table 3.4. Hydraulic Conductivity Estimate

HIL	K (gpm/ft/ft)	R/r_w	k_v (cm/sec)	k_r (cm/sec)
4	0.0051	100	$2.56x10^{-4}$	$2.56x10^{-4}$
		100	$1.00x10^{-3}$	$6.56x10^{-3}$
		100	$4.00x10^{-6}$	$1.64x10^{-2}$
		250	$3.07x10^{-4}$	$3.07x10^{-4}$
		250	$1.00x10^{-5}$	$9.42x10^{-3}$
		250	$4.00x10^{-6}$	$2.36x10^{-2}$
5	0.00035	100	$3.45x10^{-4}$	$3.45x10^{-4}$
		100	$1.00x10^{-5}$	$1.19x10^{-3}$
		100	$4.00x10^{-6}$	$2.96x10^{-2}$
		250	$4.14x10^{-4}$	$4.14x10^{-4}$
		250	$1.00x10^{-5}$	$1.71x10^{-3}$
		250	$4.00x10^{-6}$	$4.26x10^{-2}$
7	0.00025	100	$2.53x10^{-4}$	$2.53x10^{-4}$
		100	$1.00x10^{-5}$	$6.41x10^{-3}$
		100	$4.00x10^{-6}$	$1.60x10^{-2}$
		250	$3.04x10^{-4}$	$3.04x10^{-4}$
		250	$1.00x10^{-5}$	$9.21x10^{-3}$
		250	$4.00x10^{-6}$	$2.31x10^{-2}$
6	0.00030	100	$2.96x10^{-4}$	$2.96x10^{-4}$
		100	$1.00x10^{-5}$	$8.73x10^{-3}$
		100	$4.00x10^{-6}$	$2.16x10^{-2}$
		250	$3.54x10^{-4}$	$3.54x10^{-4}$
		250	$1.00x10^{-5}$	$1.26x10^{-3}$
		250	$4.00x10^{-6}$	$3.14x10^{-2}$

1×10^{-5} cm/sec. The estimated hydraulic conductivities ($(k_x k_y)^{0.5}$) were found to be more than one order of magnitude greater than the previous ACSWL k_y estimates, indicating a definite anisotropic nature of the landfill material. The anisotropy at ACSWL would result from the composition of the waste, the manner in which the waste was deposited and compacted, and the presence of sandy cover soil layers.

Summary and Conclusions

A horizontal injection leachate recycle system was successfully operated at a lined landfill in Florida. The data reported here included the construction and operation experience, and the hydraulic performance of the HI-LRS. Over a 19-month period, 7,900,000 gallons of leachate were recycled into 11 injection lines. Construction of the lines was performed by landfill operators with typical landfill equipment.

Applied injection pressures and leachate flow rates were monitored throughout all of the injection tests. The flow rate to applied pressure ratio was monitored, and decreased with time. Potential reasons for this observation were clogging of injection lines and trenches, and the large gas back-pressure observed in the lines. Substantial volumes of leachate could still be recycled to the landfill at these later times. Long term monitoring is needed to observed effects on flow rates after extended operation times. Typical values of flow response ranged from 0.008 to 0.007 gpm/ft per

foot of applied pressure head for trenches with tires as drainage material, and ranged from 0.0041 to 0.0046 for the two HIL without tires. These values were determined for flow rates ranging from 0.15 to 0.22 gpm/ft. Use of these values for flows outside this range should be performed with caution until additional data is collected. The results reported here represent the conditions at one landfill. While landfill conditions vary from site to site, these results provide a starting point for the design of a HI-LRS.

CHAPTER 4
HORIZONTAL INJECTION LEACHATE RECYCLE:
CONSTRUCTION-OPERATION GUIDELINES AND DESIGN PROCEDURE

Introduction

This paper outlines guidelines for the design, construction, and operation of horizontal injection leachate recycle systems (HI-LRS) at solid waste landfills. Horizontal injection leachate recycle is a method to recirculate collected landfill leachate back through landfilled material using horizontal wells buried within the waste. Leachate recycle offers the potential to accelerate the decomposition of biodegradable components in the landfill, to provide some measure of leachate treatment, and to provide a method of leachate volume management.

The guidelines presented here are the result of three years of work in the construction and operation of a HI-LRS at a Florida landfill (Chapter 3) and an analysis of theoretical relationships of steady-state saturated flow from a horizontal injection well (Chapter 2). The design guidelines presented apply to the sizing and placement of the landfill's hydraulic structures, specifically the LRS pumping and conveyance system, the injection lines, and the leachate collection system. Other landfill aspects not considered here, but which play a potential role in the design of such a system include

the effect of leachate recycle application rates and frequency on the landfill decomposition process, the effect of the HI-LRS on the overall hydrologic balance at the site, and the collection of landfill gas from the injection lines. This chapter provides fundamental information for the implementation of HI-LRS at solid waste landfills.

Theory of Horizontal Injection

The principles behind the leachate recycle process have been well illustrated in pilot-scale work (Leckie et al. 1979, Pohland 1980) and have been applied at numerous full-scale sites in the United States and throughout the world (Natale and Anderson 1985, Barber and Maris 1984). A variety of leachate recycle methods have been employed, each with distinct advantages and disadvantages. One method which possesses a number of advantages over other leachate recycle methods is horizontal injection. This technology utilizes perforated pipe or drainage material placed in horizontal trenches buried within the landfill waste. The trenches are constructed during the operational years of the landfill while waste is deposited.

A HI-LRS permits the recirculation of leachate to the interior of the landfill without exposure to the atmosphere. Placement of injection wells at different locations and elevations allows control of the rate and frequency of leachate application to areas within the landfill. Horizontal

injection wells present minimal interference with landfill surface operations and vehicle traffic.

Construction and Operation Guidelines

The construction of a HI-LRR requires advance planning and timing in regard to the deposition of solid waste. During the process of waste placement, a compacted layer of solid waste is often placed above the area of an injection line immediately after it is constructed, therefore operations must be timed in coordination with the landfill filling sequence. Construction in the close proximity of landfill vehicular traffic may be necessary and proper safety provisions must be made. The length of time a trench is left open should be limited to reduce odor problems, as well as to comply with regulations regarding the daily application of cover material to solid waste.

The utility of an injection line and trench as a hydraulic distribution structure should be considered during construction. In a landfill, layers of cover material are distributed throughout, and may act as preferential channels or hydraulic barriers, leading to uneven leachate distribution and surface seepage. Large pressures often develop in the area surrounding a well, and if a layer of highly permeable material intercepts a zone of high pressure, a direct seep to the surface, face, or bottom of the landfill may result. As waste is deposited around an injection well, direct contact with the soil cover material should be minimized and HIL

should be surrounded by solid waste to the greatest extent possible.

Cover materials with hydraulic properties comparable to solid waste would provide the most uniform moisture distribution. The use of an alternative daily cover such as a temporary tarp or foam would create more uniform interior landfill conditions, and minimize potential seepage channels. Short circuiting may also result from proximity to a gas well. Use of vertical gas wells in areas of injection should be limited.

Differential settlement of landfilled material should be considered in selecting pipe materials. This is most important for the non-perforated pipe section connecting the HIL to the LRS pumping system. If a drainage material is provided in the trench, hydraulic flow would still be possible in the event of a pipe break. Provision must be made to connect the injection lines to a main distribution line along the boundary of the landfill. The ends of the injection trench should be located a sufficient distance from the landfill face to minimize potential seepage. A clay seal or flow collar should be placed between the perforated distribution and non-perforated connection pipe to prevent preferential flow along the non-perforated pipe. Flexible connections from the HIL to the main distribution line should provide allowance for settlement.

The type of landfill unit also impacts the construction and use of the HI-LRS. In-ground landfills, or landfills surrounded by large earthen berms, are less likely to pose a seepage problem than high-rise landfills. In-ground landfills could be operated at greater injection flow rates than high-rise landfills. As part of HI-LRS operation, the pressure and flow of the injection system should be monitored routinely during operation. Mechanisms should exist to adjust the rate of leachate flow to maintain performance standards within the design of the system. The landfill should be inspected routinely for seepage that might be the result of the injection system, so that adjustments to the HI-LRS operation can be made.

Design Elements

In the sizing and placement of a HI-LRS, features that must be considered include:

1. Maximizing the distribution of moisture throughout the landfill.
2. Minimizing the potential for leachate seeps to the surface or side slopes of the landfill.
3. Maintaining the design performance of the leachate collection system in regard to the leachate head above the liner

To design a HI-LRS the pipes must be sized and spaced, the rate and frequency of flow application must be forecasted, and the leachate collection system must be designed to accommodate maximum design leachate recycle rates.

The volume and rate of leachate which will be recycled at a landfill is a function of the landfill's hydrology, topography, and configuration. The factors which play a large role in determining leachate recycle rates include:

1. Total volume of rainfall infiltrating into the landfill.

2. Volume of storm-water retained within the landfill unit which must be managed as leachate.

3. Leachate treatment and disposal capacity outside the landfill.

4. Leachate storage capacity at a landfill site.

The latter three factors are determined as part of the overall design process and should be evaluated in conjunction with the HI-LRS design. A hydrologic budget should be forecasted which includes the HI-LRS. Hydrologic models which incorporate rainfall, storm water runoff, and leachate recycle volumes (Schroeder et al., 1984, for example) should be employed to determine design leachate recycle rates.

Injection Line Spacing

The procedure outlined here for the sizing and spacing of the injection lines, utilizes equations which describe the saturated flow region surrounding a HIL pumped under pressure (Chapter 2). The equations were developed using a line source saturated flow solution and neglect the effect of capillary potential and dispersion. Under true operating conditions, a horizontal injection leachate recycle system at a landfill

would be operated on an intermittent basis and may not reach steady state conditions. In addition, capillary forces do play a role in moisture transport in a landfill (Korfiatis et al. 1985). However, the method outlined here is not intended as a tool to model leachate production. The intended use of these equations is to establish threshold design conditions which allow the design of the HI-LRS to perform under conditions of maximum design flow.

A schematic of the saturated flow system developed around a HI-LRS is presented in Figure 4-1. The shape of the saturated zone may be described as

$$x = \frac{q}{2\pi k_y} \tan^{-1}\left[\frac{x}{y}\sqrt{\frac{k_y}{k_x}}\right] \qquad 4\text{-}1$$

where q is the linear flow rate, k_y is the vertical hydraulic conductivity, and k_x is the horizontal hydraulic conductivity. The maximum height above the HIL may be described as

$$Y_{max} = \frac{q}{2\pi\sqrt{k_x k_y}} \qquad 4\text{-}2$$

The maximum spread of leachate may be described as

$$X_{max} = \frac{q}{2k_y} \qquad 4\text{-}3$$

The lateral distance of leachate spread at the well may be described as

$$X_{well} = \frac{q}{4k_y} \qquad 4\text{-}4$$

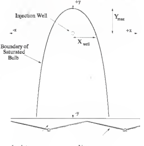


Figure 4-1- Injection Well Flow System

The above equations may be used to estimate the spacing of injection lines to maximize moisture distribution under a given set of operating conditions. Spacing may be based upon saturated zone coverage for average or peak flow conditions. The degree of overlap of zones may be selected by the design engineer based on the engineer's confidence in the design data and the flexibility of the pumping system. An additional distance of leachate spread which accounts for the unsaturated flow zone that would surround the saturated zone could be incorporated. The equations can be used to determine locations and operating conditions to minimize the potential for seepage occurring.

Design of Pumping System

The pressure required to deliver a given flow rate in a specified injection system may be determined by use of empirical data for values of injection flow rate to applied pressure ratio, defined here as κ, determined from other landfill sites. Typical values of κ measured at the Alachua County Southwest Landfill (Chapter 3) ranged from 0.005 to 0.007 gpm/ft per foot of applied pressure (water column). These measurements were made from tire-filled trenches with 3-inch PVC injection lines operated at flow rates of 0.15 to 0.22 gpm/ft. For injections lines without shredded tires, κ ranged from 0.41 to 0.46 gpm/ft per foot of applied pressure.

The pressure required to deliver a given flow rate in a specified injection system may also estimated from values for waste hydraulic conductivity using of the following equation:

$$P_h = \frac{q}{2\pi\sqrt{K_x K_y}} \ln\frac{R}{r_w} \qquad 4\text{-}5$$

where P_h is the applied pressure head, r_w is the effective well radius, and R is the radius of influence. The radius of influence may be thought of as the distance beneath a horizontal line source at which the effect of line source becomes negligible.

Using these relationships, a system curve may be established from which a pump can be selected. The system curve for steady state injection into a HIL of length L, may be determined with the following equations:

$$P_h = Z + \frac{V_p^2}{2g} + \frac{fL}{D}\frac{V_p^2}{2g} + (\Sigma K_m)\frac{V_p^2}{2g} + \frac{Q}{\kappa} \qquad 4\text{-}6$$

$$P_h = Z + \frac{V_p^2}{2g} + \frac{fL}{D}\frac{V_p^2}{2g} + (\Sigma K_m)\frac{V_p^2}{2g} + \frac{Q}{2\pi L\sqrt{k_x k_y}}\ln\left[\frac{R}{r_w}\right] \qquad 4\text{-}7$$

where V_p is the pipe velocity, Q is the injected flow rate, f is the friction factor, D is the internal pipe diameter, and ΣK_m is the sum of the minor loss coefficients.

Solid Waste Properties

The hydraulic conductivity of the landfilled solid waste must be estimated to design the injection well system. The

hydraulic conductivity of MSW has been reported in a number of studies, and the values have been found to vary greatly. A summary of reported MSW hydraulic conductivities is presented in Table 4-1 and includes information regarding the vertical hydraulic conductivity determined at the ACSWL in a previous study (Townsend et al. In press a). Also included in Table 4-1 are the estimated $(k_x k_y)^{0.5}$ values resulting from the horizontal injection experiment at ACSWL (Chapter 3).

Since hydraulic conductivity values are the greatest unknown in this process, the pumping system should be designed to allow flexible control over the injected pressures and flow rates over an expected range of conditions. No landfill is homogeneous and this uncertainty requires that some degree of operational control be available after the system is in place.

Leachate Collection System

Typical design of a leachate collection system (LCS) includes performing simulations with a hydrologic model to determine an infiltration rate for leachate into the leachate collection system drainage layer. From this, the head above the liner may be determined as a function of the characteristics of the LCS using a number of equations (Moore 1980, McEnroe 1994). In the design of an HI-LRS, the equations developed for the shape of the saturated flow zone may be employed to estimate the infiltration of leachate into the LCS. This allows the effect of continuous injection at large pressures to be predicted.

Table 4-1 Solid Waste Hydraulic Conductivity

Source	Comment	Hydraulic Conductivity (cm/sec)
Fungaroli and Steiner (1979)	Laboratory Tests, Shredded Waste	$1x10^{-4}$ - $2x10^{-2}$
Korfiatis et al. (1984)	Laboratory Tests	$8x10^{-3}$ - $2x10^{-2}$
Oweis et al. (1990)	Laboratory Tests	$1.5x10^{-4}$
Oweis et al. (1990)	Landfill Pump Test	$1x10^{-3}$ - $2.5x10^{-3}$
Schroeder (1985)	HELP Model Default Value	$2x10^{-4}$
Townsend et al. (1995)	Landfill Test, Infiltration Ponds ACSWL k_v	$3x10^{-6}$ - $4x10^{-4}$
Shank (1993)	Landfill Pump Test ACSWL k_h	$6.7x10^{-5}$ - $4x10^{-3}$
This Study (Chapter 3)	Estimate from HI-LRS ACSWL $(k_h k_v)^{0.5}$	$2.5x10^{-4}$ - $3.5x10^{-4}$ *

* Based on R/r_w = 100

At an infinite distance beneath a horizontal injection well, the downward infiltration will equal the injected flow, or q/k_y. The closer the LCS is located to the injection well, the greater the infiltration rate of leachate per unit area into the leachate collection system. This flow rate, or infiltration rate into the LCS, may be determined for the entire width of the saturated zone using the following equation and Eqn. 4-1, to determine $x(y)$:

$$q(y) = \frac{2X_{max}}{x(y)} \frac{q}{k_y} \qquad 4\text{-}8$$

In the design of a LCS, simulations should be performed which predict leachate head above the liner resulting from site rainfall at times when the depth of waste is small. The maximum conditions developed in the injection system should then be tested to determine if the liner design requirements are met.

Conclusion

A method was outlined to design a horizontal injection leachate recycle system. The design was based on the hydraulic sizing and spacing of the injection lines to maximize the distribution of leachate while minimizing potential for surface seepage. The procedure involved the use of steady-state saturated flow equations to approximate the spread of the saturated zone surrounding an injection line.

The prediction of leachate generation rates and moisture movement rates requires the use of more sophisticated numerical models, which account for the many complexities of a landfill.

Additional factors may affect the design and operation of a HI-LRS. The method outlined here should provide guidelines for HI-LRS design, and which should allow flexibility to examine various scenarios to meet specific goals in HI-LRS design. Additional work in the application of this technology to other sites will aid in the determination of the effects of the many additional factors that will ultimately require consideration.

CHAPTER 5
SUMMARY AND CONCLUSIONS

This dissertation reviewed the use of a technology known as horizontal injection leachate recycle. This technology utilizes horizontal wells constructed in the solid waste of a landfill to allow recirculation of leachate to the landfilled waste. The advantages of leachate recycle are many, and include the following.

1. Leachate recycle provides a means of hydrologic management at landfill sites.

2. The recirculation of leachate promotes the acceleration of biological stabilization of the solid waste.

3. Recycled leachate receives some treatment from the biologically active landfill.

4. A landfill which has been biologically stabilized presents a substantially reduced risk to the environment as a result of landfill operations.

5. Biological stabilization may obviate the need for landfill closure and may allow the reclamation of stabilized material.

Horizontal injection is one of several methods of leachate recycle, and the advantages of this method include

1. Leachate may be recycled to the landfill without direct exposure to the atmosphere.

2. The point of leachate application may be controlled, allowing the flexibility to target specific areas and

levels within the landfill, as well as the rate and frequency of application.

3. Horizontal injection wells have little impact on daily landfill operations in regard to surface area requirements and the movement of landfill vehicles and equipment.

4. Horizontal injection wells allow the addition of various chemical or biological additives to the landfill.

The major limitation for the application of horizontal injection at full-scale landfills is the lack of full-scale operational experience to provide the design, construction, and operation guidelines. This study was designed to provide such information.

A method of analyzing the predicted zones of saturated flow resulting from the injection of leachate into a porous medium was analyzed by treating the injection line as a line source. To facilitate the solution in the form of simple analytical equations, capillary forces and dispersion were neglected. The resulting solution was useful for predicting flow boundaries for maximum flow conditions which could be used in design, but was not intended to model leachate moisture transport in complex systems. Equations were developed for isotropic and anisotropic media to determine the steady state zone of saturation surrounding an injection well resulting from injection at a given flow rate.

This study reviewed the construction and operation of a HI-LES at a composite lined, operating landfill in Florida. Construction of injection lines at the Florida landfill began

in 1992, and the first injection began in 1993. Through August 1994, a total of 7,900,000 gallons of leachate were recirculated into 11 injection lines. The system was successful in providing a means of recycling large volumes of leachate to the landfill. The most dramatic problem associated with the operation of the HI-LRS was the short-circuiting of leachate to the surface through permeable zones in the landfill. Typical leachate flow rates ranged from 0.004 to 0.007 gpm/ft per foot of applied head at a flow range of 1.5 to 2.2 gpm/ft. Injection flow did decrease over time to a limited extent.

This document outlined guidelines for the design, construction, and operation of HI-LRS at full-scale landfills. The information gathered in the field research project and the theoretical flow equations were used to outline a preliminary design technique and procedure. The technique was developed to allow estimates for the spacing of injection lines, placement and operation of lines to preclude the seepage of leachate to the surface, and the placement and operation of lines for the design of leachate collection systems. The procedures outlined are proposed as a method for the design and operation of a HI LRS which in turn will allow additional field data to be gathered for the refinement of the design of such systems.

The operation and design of horizontal injection leachate recycle systems were reviewed in regard to the hydraulic

design of the landfill components (LRS piping and pump sizing, LCS design). Additional areas that influence the design of an injection system may include:

1. The effect of leachate application on biological activity of the landfill microorganisms.

2. The hydrology of the entire landfill site.

3. Use of the HILs to collect landfill gas.

4. The effect of leachate recycle on leachate quality.

Additional field studies at the site discussed here and other sites is necessary for further development of this system.

APPENDIX A
LEACHATE INJECTION GRAPHS

This appendix presents graphs of the data collected for the horizontal injection line tests at ACSWL. The results cover injection lines 1 through 11, and cover a period from February 1993 through August 1994. The following graphs are presented for each injection line

I. Injection flow and pressure versus calendar time (day 1 represents January 1, 1993).

II. Injection flow and pressure versus pumping time.

III. Linear flow rate and total energy head at entrance of injection line versus pumping time.

IV. Linear flow rate:total energy head ratio (κ) versus pumping time.

Gaps in the data in graphs of pumping time and cumulative pumped volume represents injection tests where data logger files were lost. Total volume and pumping time were accounted for in these cases.

Legend: The following graphs were formatted so flow is reported by the thicker solid line and pressure by the thinner dotted line. The flow is generally scaled higher than the pressure.

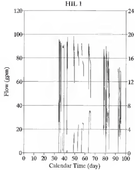


Figure A-1. Injection Flow Rate and Pressure versus Calendar Time: HIL 1 (February 1993 - April 1993)

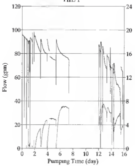


Figure A-2 Injection Flow Rate and Pressure versus Injection Time: HIL 1 (February 1993 - April 1993)

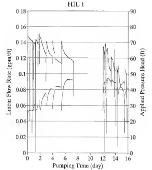


Figure A-3. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 1 (February 1993 - April 1993)

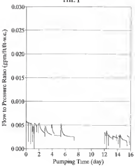


Figure A-4. κ versus Injection Time: HIL 1
(February 1993 - April 1993)

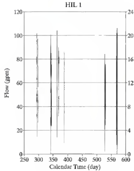


Figure A-5. Injection Flow Rate and Pressure versus Calendar Time: HIL 1 (September 1993 - August 1994)

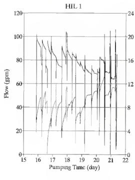


Figure A-6 Injection Flow Rate and Pressure versus Injection Time: HIL 1 (September 1993 - August 1994)

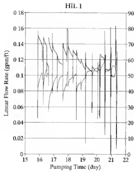


Figure A-7. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 1 (September 1993 - August 1994)

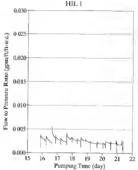


Figure A-8. κ versus Injection Time: HIL 1 (September 1993 - August 1994)

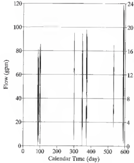


Figure A-9. Injection Flow Rate and Pressure versus Calendar Time: HIL 2

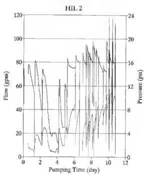


Figure A-10. Injection Flow Rate and Pressure versus Injection Time: HIL 2

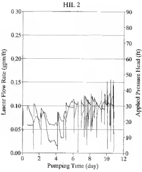


Figure A-11. Linear Flow Rate and Total Applied Head versus Injection Time; HIL 2

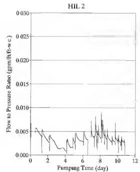


Figure A-12. κ versus Injection Time: HIL 2

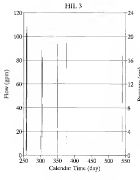


Figure A-13. Injection Flow Rate and Pressure versus Calendar Time: HIL 3

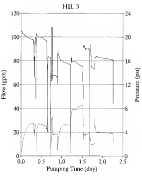


Figure A-14. Injection Flow Rate and Pressure versus Injection Time, HIL 3

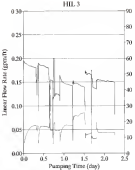


Figure A-15. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 3

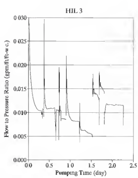


Figure A-16. κ versus Injection Time: HIL 3

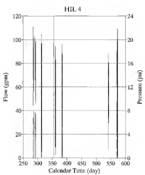


Figure A-17. Injection Flow Rate and Pressure versus Calendar Time: HIL 4

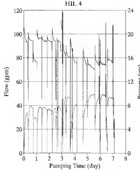


Figure A-18. Injection Flow Rate and Pressure versus Injection Time: HIL 4

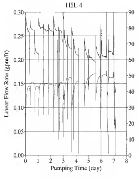


Figure A-19. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 4

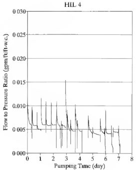


Figure A-20. κ versus Injection Time: HIL 4

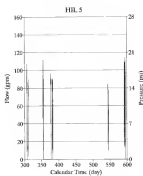
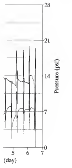


Figure A-21. Injection Flow Rate and Pressure versus Calendar Time: HIL 5



te and Pressure versus
HIL 5

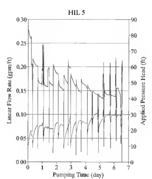


Figure A-23. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 5

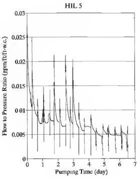


Figure A-24. κ versus Injection Time: HIL 5

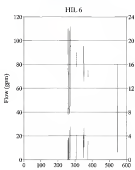


Figure A-25 Injection Flow Rate and Pressure versus Calendar Time, HIL 6

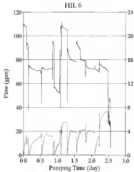


Figure A-26. Injection Flow Rate and Pressure versus Injection Time: HIL 6

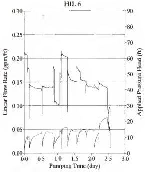


Figure A-27. Linear Flow Rate and Total Applied Head versus Injection Time, HIL 6

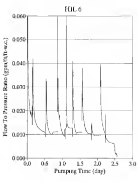


Figure A-28. K versus Injection Time: HIL 6

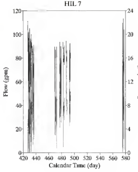


Figure A-29. Injection Flow Rate and Pressure versus Calendar Time: HIL 7

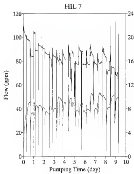


Figure A-30. Injection Flow Rate and Pressure versus Injection Time: HIL 7

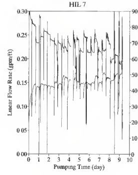


Figure A-31. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 7

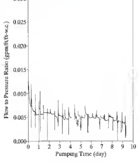


Figure A-32. x versus Injection Time HIL 7

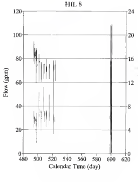


Figure A-33. Injection Flow Rate and Pressure versus Calendar Time: HIL 8

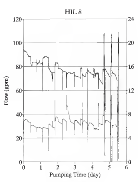


Figure A-34. Injection Flow Rate and Pressure versus Injection Time, HIL 8

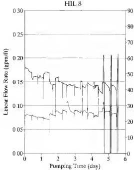


Figure A-35. Linear Flow Rate and Total Applied Head versus Injection Time; HIL 8

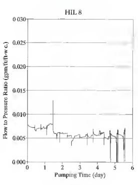


Figure A-36. κ versus Injection Time: HIL 8

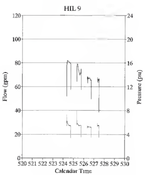


Figure A-37: Injection Flow Rate and Pressure versus Calendar Time: HIL 9

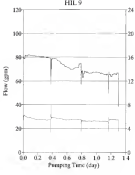


Figure A-36. Injection Flow Rate and Pressure versus Injection Time: HIL 9

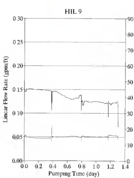


Figure A-39. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 9

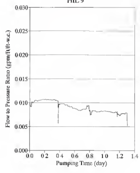


Figure A-40. κ versus Injection Time: HIL 9

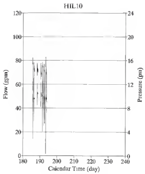


Figure A-41. Injection Flow Rate and Pressure versus Calendar Time: HIL 10

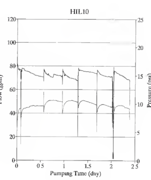


Figure A-42. Injection Flow Rate and Pressure versus Injection Time, HIL 10

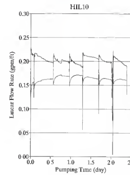


Figure A-43 Linear Flow Rate and Total Applied Head versus Injection Time, HIL 10

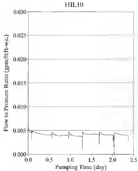


Figure A-44. κ versus Injection Time: HIL 10

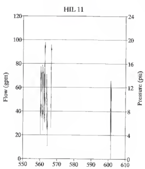


Figure A-45. Injection Flow Rate and Pressure versus Calendar Time, HIL II

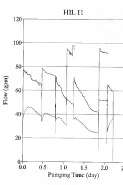


Figure A-46. Injection Flow Rate and Pressure versus Injection Time: HIL I1

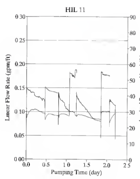


Figure A-47. Linear Flow Rate and Total Applied Head versus Injection Time: HIL 11

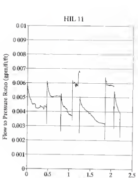


Figure A-48: κ versus Injection Time: HIL 11

LITERATURE CITED

Barber, C. and P. J. Maris (1984). "Recirculation of leachate as a landfill management option: benefits and operational problems." *Quarterly Journal of Engineering Geology, London*, 17, 19-29.

Baar, J. and G. Dagan (1965). "The relationship between solutions flow problems in isotropic and anisotropic soils." *Journal of Hydrology*, 3, 69-96.

Bear, J. and M. Jacobs (1965). "On the movement of water bodies injected in aquifers." *Journal of Hydrology*, 3, 37-57.

Bear, J. (1979). *Hydraulics of Groundwater*, McGraw-Hill Publishing Company, New York, NY.

Buivid, M. G., D. L. Wise, M. J. Blanchet, E. C. Remedios, B. M. Jenkins, W. F. Boyd, and J. G. Pacey (1981). "Fuel gas enhancement by controlled landfilling of municipal solid waste." *Resources and Conservation*, 6, 3-20.

Carslaw, H. S. and J. C. Jaeger J. C. (1959). *Conduction of Heat in Solids, 2nd Edition*, Oxford University Press, London, England.

Federal Register (1991). 56(No. 196, October 9) 51055.

Fungaroli, A. A. and R. L. Steiner (1979). "Investigation of sanitary landfill behavior." EPA-6001/2-79-053a. U. S. Environmental Protection Agency, Cincinnati, OH.

Javandel, I. and T. Chin-Fu (1986) "Capture-zone type curves: A tool for aquifer cleanup." *Ground Water*, 24(5), 616-625.

Korfiatis, G. P., A. C. Demetracopolous, E. L. Bourodimos, and E. G. Nawey (1984). "Moisture transport in a solid waste column." *Journal of Environmental Engineering, ASCE*, 110, 4, 780-796.

Leckie, J. O., J. G. Pacey and C. Halvadakis (1979). "Landfill management with moisture control." Journal of Environmental Engineering, ASCE, 105, EE2

McEnroe, B. M. (1989). "Steady drainage of landfill covers and bottom liners." Journal of Environmental Engineering, ASCE, 115(6), 1114-1122.

Moore, C. A. (1983). "Landfill and surface impoundments evaluation." EPA/530/SW-869-C, U. S. Environmental Protection Agency, Cincinnati, OH.

Natale, B. R. and W. C. Anderson (1985). Evaluation of a landfill with leachate recycle: preliminary report. Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC

Oweis, I. S., D. A. Smith, R. B. Ellwood, D. S. Greene (1990). "Hydraulic characteristics of municipal refuse." Journal of Geotechnical Engineering, ASCE, 116, 4, 539-553.

Philip, J. R. (1971). "General theorem on steady infiltration from surface sources, with application to point and line sources." Soil Science Society of America Proceedings, 35, 867-871.

Pohland, F. G. (1975). Sanitary landfill stabilization with leachate recycle and residual treatment. EPA-600/2-75-043, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Pohland, F. G. (1980). "Leachate recycle as a management option." Journal of Environmental Engineering, ASCE, 106, EE6, 1057-1089.

Raats, P. A. C. (1970). "Steady infiltration from line sources and furrows." Soil Science Society of America Proceedings, 34(5), 709-714.

Schroeder, P. R., J. M. Morgan, T. M. Walski, and A. C. Gibson (1984). Hydrologic evaluation of landfill performance (HELP) model: Vol. II; Users guide for version I. EPA/530-SW-84-010, U.S. Environmental Protection Agency, Washington, DC.

Shenk, K. L. (1993). "Determination of hydraulic conductivity of the Alachua County Southwest Landfill." Master's thesis, University of Florida.

Thomas, A. W., E. G. Kruse, and H. R. Duke (1974). "Steady infiltration from line sources buried in soil." Transactions of the American Society of Agricultural Engineers, 17, 125-133.

Townsend, T. G., W. L. Miller, J. F. K. Earle (In press a). "Leachate recycle infiltration ponds." to be published in Journal of Environmental Engineering, ASCE.

Townsend, T. G., W. L. Miller, J. F. K. Earle, Lee H. (In press b). "Acceleration of solid waste stabilization at a Florida landfill using leachate recycle." to be published in Journal of Environmental Engineering, ASCE.

Watson, R. P. (1987). "A case study of leachate generation and recycling at two sanitary landfills" in Proceedings from the Technical Sessions of the GRCDA 25th Annual International Seminar, Equipment, Services, and Systems Show. Vol. 2, August 11-13, Saint Paul, MN.

Zachmann, D. W., and A. W. Thomas (1973). "A mathematical investigation of steady infiltration from line sources." Soil Science Society of America Proceedings, 37, 495-500.

BIOGRAPHICAL SKETCH

Timothy G. Townsend was born in San Diego, California, on October 17, 1967, to Timothy A. and Cynthia Townsend. He graduated from Orange Park High School in Orange Park, Florida, in 1985.

He enrolled in the University of Florida in September, 1985, and graduated with high honors with a Bachelor of Science degree from the Department of Environmental Engineering Sciences in December 1989. He enrolled in graduate school in the same department in January, 1990, to study solid and hazardous waste. He graduated with his Master of Engineering degree in December, 1992.

Tim was married to Marlene Elizabeth on March 14, 1991.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Professor of Environmental Engineering Sciences

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